

Definition

In contrast to a conventional programming language which are (typically) used to describe software, a **Hardware Description Language (HDL)** is used to describe (or model) hardware (e.g., digital logic).

► (Selected) **examples**:

1. Verilog
2. VHDL
3. MyHDL ⊃ Python
4. Chisel ⊃ Scala
- ⋮

► **Agenda: Verilog**, or, more specifically,

1. foundational concepts,
2. low-level modelling,
3. high-level modelling, and
4. development concepts, e.g., testing and test stimuli.

► **Caveat!**

1. Verilog $\equiv$ “classic” Verilog-2005 per IEEE 1364-2005 [5]
2. 3 lectures $\Rightarrow$ introductory coverage of *core* language features and workflow
3. learning $\Leftarrow$ theory *and* practice (or application)

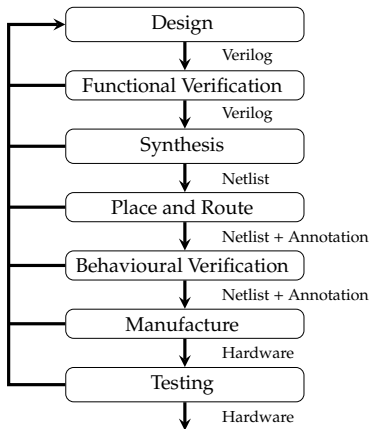
Part 1: foundational concepts (1)

- ▶ **Question:** *why?!*
- ▶ **Answer:** HDLs (and EDA tools more generally) help to
 1. facilitate automation, e.g., with respect to
 - ▶ simulation,
 - ▶ verification, and
 - ▶ translationof what is a more clearly machine-readable design,
 2. address the challenge of scale, e.g., with respect to design size and complexity.

Part 1: foundational concepts (2)

► **Question:** *how?!*

► **Answer:** as part of a broader development workflow, such as



► You can think of

synthesis $\approx$ compilation
place and route $\approx$ linking

since

- the former translates from high- to low-level, in this case a HDL model to a gate-level netlist,
- the latter works out how to use the standard cell library (e.g., the type and location of gates).
- Verification steps rely on simulation of the model at different levels of detail.

Part 1: foundational concepts (3)

► Analogy:

C	Verilog
► A program is described using static function definitions. ► Each function has an interface (i.e., what it does and how it can be used) and a body (i.e., how it does it). ► The functions reference each other via calls; a function call implies an active, <i>transient</i> use. ► Values are stored in variables, on which computation is performed by functions.	► A model is described using static module definitions. ► Each module has an interface (i.e., what it does and how it can be used) and a body (i.e., how it does it). ► The modules reference each other via instantiations; a module instantiation implies an active, <i>permanent</i> use. ► Values are carried by nets, on which computation is performed by modules.

but, beware:

- on one hand, the analogy is attractive if you have some C programming experience, *but*
- on the other hand, the analogy is unattractive (perhaps even *dangerous*) because it's *imperfect* in various ways.

Part 1: foundational concepts (4)

► Example:

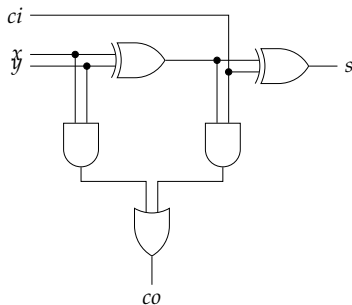
```
module fa( output wire co,
           output wire s,
           input wire ci,
           input wire x,
           input wire y );

  wire w0, w1, w2;

  xor t0( w0, x, y );
  and t1( w1, x, y );

  xor t2( s, w0, ci );
  and t3( w2, w0, ci );

  or t4( co, w1, w2 );
endmodule
```



Part 1: foundational concepts (5)

- **Example:** a model can be described in
 1. a high-level, behaviour-oriented style, or
 2. a low-level, implementation-oriented style, or
 3. a *hybrid* of the two

so, e.g.,

Option #1: switch-level Verilog

At the lowest-level, the model can be described using individual transistors. For example, the four transistor instances

```
pmos( t, VDD, b );  
pmos( a, t, c );  
nmos( a, VSS, c );  
nmos( a, VSS, b );
```

replicate the previous circuit for a MOSFET-based NOR gate, meaning they continuously drive the wire a with the the result of evaluating $\neg(b \vee c)$.

Part 1: foundational concepts (5)

- **Example:** a model can be described in
1. a high-level, behaviour-oriented style, or
 2. a low-level, implementation-oriented style, or
 3. a *hybrid* of the two

so, e.g.,

Option #2: gate-level Verilog

Forces the model to be described at a low-level, using only primitive logic gates (e.g., AND, OR, NOT). For example, the gate instantiation

```
nor t( a, b, c );
```

continuously drives the wire a with the the result of evaluating $\neg(b \vee c)$.

Part 1: foundational concepts (5)

- **Example:** a model can be described in
1. a high-level, behaviour-oriented style, or
 2. a low-level, implementation-oriented style, or
 3. a *hybrid* of the two

so, e.g.,

Option #3: Register Transfer Level (RTL) Verilog

Uses a syntax similar to C, but focuses on describing the model in terms of the data-flow between components rather than high-level statements. For example, the continuous assignment

```
assign a = ~( b | c )
```

continuously drives the wire a with the the result of evaluating $\neg(b \vee c)$.

Part 1: foundational concepts (5)

- **Example:** a model can be described in
 1. a high-level, behaviour-oriented style, or
 2. a low-level, implementation-oriented style, or
 3. a *hybrid* of the two

so, e.g.,

Option #4: behavioural-level Verilog

Allows a high-level, C-style description of the model using assignments, loops and conditional statements. For example, the procedural assignment

$$a = \sim(b \mid c)$$

sets the register `a` equal to the result of evaluating $\neg(b \vee c)$.

Part 2: low-level modelling (1)

Wires and values

► **Concept: wires** (resp. **wire vectors**)

► are a form of **net** used to *communicate* values,

► e.g.,

- `wire w` $\Rightarrow$ an internal 1-bit wire `w`
- `wire [ 3 : 0 ] x` $\Rightarrow$ an internal 4-bit wire vector `x`
- `input wire [ 3 : 0 ] y` $\Rightarrow$ an input 4-bit wire vector `y`
- `output wire [ 3 : 0 ] z` $\Rightarrow$ an output 4-bit wire vector `y`

Part 2: low-level modelling (2)

Wires and values

► Concept: values

1. support the concept of 3-state logic, e.g.,
 - $0 \Rightarrow 0$ (i.e., logical **false**)
 - $1 \Rightarrow 1$ (i.e., logical **true**)
 - $X \Rightarrow$ unknown (i.e., neither 1 or 0)
 - $Z \Rightarrow$ high impedance (i.e., disconnected)
2. can be written in binary, decimal, or hexadecimal, e.g.,
 - $2'b10 \Rightarrow$ a 2-bit binary literal, with value $10_{(2)}$, $2_{(10)}$, or $2_{(16)}$
 - $8'd17 \Rightarrow$ a 8-bit decimal literal, with value $00010001_{(2)}$, $17_{(10)}$, or $11_{(16)}$
 - $4'hF \Rightarrow$ a 4-bit hexadecimal literal, with value $1111_{(2)}$, $15_{(10)}$, or $F_{(16)}$
3. can include 3-state values on a per-bit basis, e.g.,
 - $1'bX \Rightarrow$ a 1-bit binary literal; the bit is unknown
 - $4'b10XZ \Rightarrow$ a 4-bit binary literal; the bits are high impedance, unknown, 0, and 1

Part 2: low-level modelling (3)

Wires and values

► Analogy:

C

- The definition

`char u` $\rightsquigarrow$ 8 *separate* 1-bit elements

but `u` is typically used as 1 *single* 8-bit object.

- The definition

`char v[ 32 ]` $\rightsquigarrow$ 32 *separate* 8-bit elements

and `v` is typically used as 32 *separate* 8-bit elements.

Verilog

- The definition

`wire x` $\rightsquigarrow$ 1 *single* 1-bit wire

and `u` is used as 1 *single* 1-bit object.

- The definition

`wire [ 3 : 0 ] y` $\rightsquigarrow$ 4 *separate* 1-bit wires

such that

1. `y` can be used as 1 *single* 4-bit object, *or*
2. `y` can be used as 4 *separate* 1-bit wires.

but, beware:

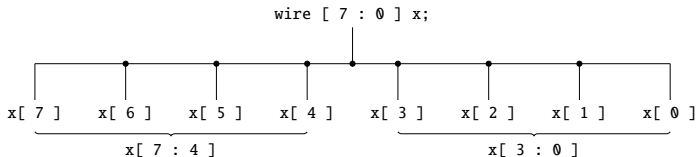
- a wire (resp. wire vector) cannot retain state (e.g., doesn't behave like a C variable),
- we need to *drive* a value on it.

Part 2: low-level modelling (4)

Wires and values

► Concept: subscript operator.

- consider a case where $x = 8'b11110000$, and



► we have that

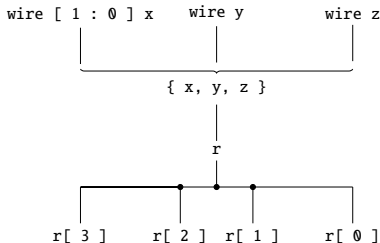
- `x[ 7 ]`, `x[ 6 ]`, `x[ 5 ]` and `x[ 4 ]` are all 1-bit wires with value `1'b1`,
- `x[ 3 ]`, `x[ 2 ]`, `x[ 1 ]` and `x[ 0 ]`, are all 1-bit wires with value `1'b0`,
- `x[ 7 : 4 ]` is a 4-bit wire vector with value `4'b1111`, and
- `x[ 3 : 0 ]` is a 4-bit wire vector with value `4'b0000`.

Part 2: low-level modelling (5)

Wires and values

► **Concept: concatenate operator.**

- consider a case where $x = 2'b10$, $y = 1'b1$, and $z = 1'b0$, and



► we have that

- { x, y, z } is a 4-bit wire vector with value $4'b1010$,
- $r[3]$ is a 1-bit wire with value $1'b1$ (matching $x[1]$),
- $r[2]$ is a 1-bit wire with value $1'b0$ (matching $x[0]$),
- $r[1]$ is a 1-bit wire with value $1'b1$ (matching y), and
- $r[0]$ is a 1-bit wire with value $1'b0$ (matching z).

Part 2: low-level modelling (7)

Modules

► **Concept:** module **definition**

- are a passive (or static) *description* of a component,
- e.g.,

Listing (Verilog)

```
1 module mux2_1bit( output wire r,  
2                   input  wire c,  
3                   input  wire x,  
4                   input  wire y );  
5  
6   ...  
7  
8 endmodule
```

Listing (Verilog)

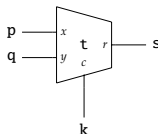
```
1 module mux2_1bit( r, c, x, y );  
2  
3   output wire r;  
4   input  wire c;  
5   input  wire x;  
6   input  wire y;  
7  
8   ...  
9  
10 endmodule
```

noting the two forms are equivalent.

► **Concept:** module **instantiation**

- are an active (or dynamic) *use* of a component,
- e.g.,

```
mux2_1bit t( s, k, p, q );
```



where we've

- created an instance of the `mux2_1bit` module identified by `t`, and
- connected the internal ports `r`, `c`, `x` and `y` to the external wires `s`, `k`, `p` and `q`

Part 2: low-level modelling (9)

Modules

► Analogy:

C

- A caller function invokes (or calls) a callee function.
- 1 *shared* copy of a callee function is used by n invocations.
- Each invocation executes in *sequence*, and *discontinuously*.

Verilog

- A instanciator module instantiates a instantiatee module.
- n *separate* copies of a instantiatee module are produced by n instantiations.
- Each instance operates in *parallel*, and *continuously*.

► Concept: gate-level module implementation

- describes module behaviour via
 1. primitive (or built-in) modules, and/or
 2. other user-defined modules,
- e.g.,

<code>buf t0(r, x);</code>	$\mapsto$	$r = x$
<code>not t1(r, x);</code>	$\mapsto$	$r = \neg x$
<code>nand t2(r, x, y);</code>	$\mapsto$	$r = x \overline{\wedge} y$
<code>nor t3(r, x, y);</code>	$\mapsto$	$r = x \overline{\vee} y$
<code>and t4(r, x, y);</code>	$\mapsto$	$r = x \wedge y$
<code>or t5(r, x, y);</code>	$\mapsto$	$r = x \vee y$
<code>xor t6(r, x, y);</code>	$\mapsto$	$r = x \oplus y$

noting that multi-input variants such as

<code>xor t8(r, w, x, y);</code>	$\mapsto$	$r = w \oplus x \oplus y$
<code>xor t9(r, w, x, y, z);</code>	$\mapsto$	$r = w \oplus x \oplus y \oplus z$

are automatically available.

► Concept: User-Defined Primitives (UDPs)

- describe module behaviour via a truth table,
- doing so assumes it models a Boolean function of the form

$$f : \{0, 1\}^n \rightarrow \{0, 1\}$$

- e.g.,

Listing (Verilog)

```
1 primitive mux2_1bit( output r,  
2                     input c,  
3                     input x,  
4                     input y );  
5     table  
6         0 0 ? : 0;  
7         0 1 ? : 1;  
8         1 ? 0 : 0;  
9         1 ? 1 : 1;  
10    endtable  
11  
12 endprimitive
```

Truth table

c	x	y	r
0	0	?	0
0	1	?	1
1	?	0	0
1	?	1	1

which can then be used in the same way as a user-defined module.

Part 2: low-level modelling (12)

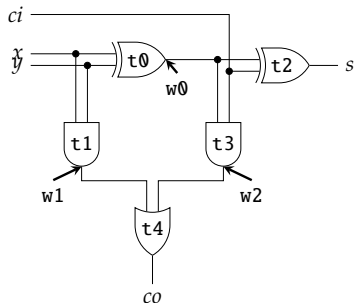
Module implementation using gate-level Verilog

► Example:

Listing (Verilog)

```
1 module fa( output wire co,
2           output wire s,
3           input wire ci,
4           input wire x,
5           input wire y );
6
7   wire w0, w1, w2;
8
9   xor t0( w0,  x,  y );
10  and t1( w1,  x,  y );
11
12  xor t2( s,  w0, ci );
13  and t3( w2, w0, ci );
14
15  or  t4( co, w1, w2 );
16
17 endmodule
```

Circuit (full-adder)



Part 2: low-level modelling (13)

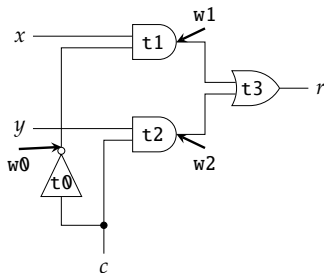
Module implementation using gate-level Verilog

► Example:

Listing (Verilog)

```
1 module mux2_1bit( output wire r,  
2                   input wire c,  
3                   input wire x,  
4                   input wire y );  
5  
6   wire w0, w1, w2;  
7  
8   not t0( w0, c );  
9  
10  and t1( w1, x, w0 );  
11  and t2( w2, y, c );  
12  
13  or t3( r, w1, w2 );  
14  
15 endmodule
```

Circuit (2-input, 1-bit multiplexer)



Part 2: low-level modelling (14)

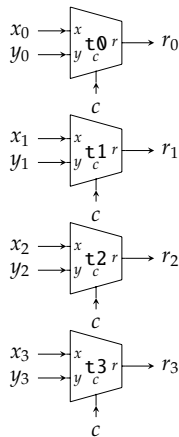
Module implementation using gate-level Verilog

► Example:

Listing (Verilog)

```
1 module mux2_4bit( output wire [ 3 : 0 ] r,  
2                 input wire    c,  
3                 input wire [ 3 : 0 ] x,  
4                 input wire [ 3 : 0 ] y );  
5  
6     mux2_1bit t0( r[ 0 ], c, x[ 0 ], y[ 0 ] );  
7     mux2_1bit t1( r[ 1 ], c, x[ 1 ], y[ 1 ] );  
8     mux2_1bit t2( r[ 2 ], c, x[ 2 ], y[ 2 ] );  
9     mux2_1bit t3( r[ 3 ], c, x[ 3 ], y[ 3 ] );  
10  
11 endmodule
```

Circuit (2-input, 4-bit multiplexer)



Part 2: low-level modelling (15)

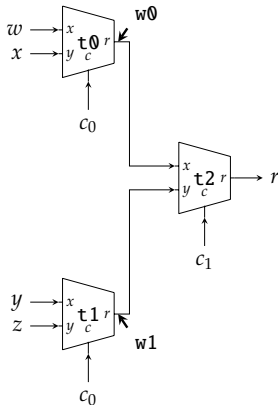
Module implementation using gate-level Verilog

► Example:

Listing (Verilog)

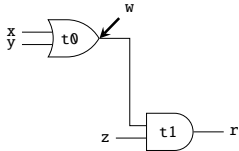
```
1 module mux4_1bit( output wire r,  
2                   input wire c0,  
3                   input wire c1,  
4                   input wire w,  
5                   input wire x,  
6                   input wire y,  
7                   input wire z );  
8  
9   wire w0, w1;  
10  
11  mux2_1bit t0( w0, c0, w, x );  
12  mux2_1bit t1( w1, c0, y, z );  
13  mux2_1bit t2( r, c1, w0, w1 );  
14  
15 endmodule
```

Circuit (4-input, 1-bit multiplexer)



- **Concept: Register Transfer Level (RTL) module implementation**

- ▶ describes module behaviour via
 1. a set of **continuous assignments**, plus
 2. any additional gate-level description
- ▶ e.g.,

$$\text{assign } r = (x \mid y) \ \& \ z; \quad \mapsto \quad \begin{array}{l} \text{or } t0(w, x, y); \\ \text{and } t1(r, w, z); \end{array} \quad \mapsto$$


- ▶ the LHS *must* be a wire or wire vector, whereas
- ▶ the RHS can contain many C-style operators
 - ▶ **arithmetic operators**, e.g., +, -, and *,
 - ▶ **logical operators**, e.g., <<, >>, ~, &, |, and ^,
 - ▶ **comparison operators**, e.g., ==, >, and <.

involving wires or wire vectors as operands.

but, beware:

- ▶ it's tempting to think of this as analogous to a C assignment,
- ▶ this is dangerous, because the RTL version is *continuous*.

► **Concept: reduction operator.**

- consider a case where wire [3 : 0] x, wire [3 : 0] y, and wire c,
- we have that

$$\text{^x} \mapsto ((x[3] \text{ ^ } x[2]) \text{ ^ } x[1]) \text{ ^ } x[0]$$

so is analagous to reduce (or foldr) in Haskell.

► **Concept: ternary operator.**

- consider a case where wire [3 : 0] x, wire [3 : 0] y, and wire c,
- we have that

$$c ? y : x \mapsto \begin{cases} x & \text{if } c = 0 \\ y & \text{if } c = 1 \end{cases}$$

so is analagous to a 2-input multiplexer.

► Example:

Listing (Verilog)

```
1 module fa( output wire co,
2           output wire s,
3           input wire ci,
4           input wire x,
5           input wire y );
6
7   wire w0, w1, w2;
8
9   xor t0( w0, x, y );
10  and t1( w1, x, y );
11
12  xor t2( s, w0, ci );
13  and t3( w2, w0, ci );
14
15  or t4( co, w1, w2 );
16
17 endmodule
```

Listing (Verilog)

```
1 module fa( output wire co,
2           output wire s,
3           input wire ci,
4           input wire x,
5           input wire y );
6
7   wire [ 1 : 0 ] t;
8
9   assign t = ci + x + y;
10
11  assign s = t[ 0 ];
12  assign co = t[ 1 ];
13
14 endmodule
```

► Example:

Listing (Verilog)

```
1 module fa( output wire co,
2           output wire s,
3           input wire ci,
4           input wire x,
5           input wire y );
6
7   wire w0, w1, w2;
8
9   xor t0( w0, x, y );
10  and t1( w1, x, y );
11
12  xor t2( s, w0, ci );
13  and t3( w2, w0, ci );
14
15  or t4( co, w1, w2 );
16
17 endmodule
```

Listing (Verilog)

```
1 module fa( output wire co,
2           output wire s,
3           input wire ci,
4           input wire x,
5           input wire y );
6
7   assign { co, s } = ci + x + y;
8
9 endmodule
```

► Example:

Listing (Verilog)

```
1 module mux2_1bit( output wire r,
2                   input wire c,
3                   input wire x,
4                   input wire y );
5
6   wire w0, w1, w2;
7
8   not t0( w0, c );
9
10  and t1( w1, x, w0 );
11  and t2( w2, y, c );
12
13  or t3( r, w1, w2 );
14
15 endmodule
```

Listing (Verilog)

```
1 module mux2_1bit( output wire r,
2                   input wire c,
3                   input wire x,
4                   input wire y );
5
6   assign r = c ? y : x;
7
8 endmodule
```

Part 2: low-level modelling (21)

Module implementation using RTL-level Verilog

► Example:

Listing (Verilog)

```
1 module mux2_4bit( output wire [ 3 : 0 ] r,  
2                 input wire    c,  
3                 input wire [ 3 : 0 ] x,  
4                 input wire [ 3 : 0 ] y );  
5  
6     mux2_1bit t0( r[ 0 ], c, x[ 0 ], y[ 0 ] );  
7     mux2_1bit t1( r[ 1 ], c, x[ 1 ], y[ 1 ] );  
8     mux2_1bit t2( r[ 2 ], c, x[ 2 ], y[ 2 ] );  
9     mux2_1bit t3( r[ 3 ], c, x[ 3 ], y[ 3 ] );  
10  
11 endmodule
```

Listing (Verilog)

```
1 module mux2_4bit( output wire [ 3 : 0 ] r,  
2                 input wire    c,  
3                 input wire [ 3 : 0 ] x,  
4                 input wire [ 3 : 0 ] y );  
5  
6     assign r = c ? y : x;  
7  
8 endmodule
```

► Example:

Listing (Verilog)

```
1 module mux4_1bit( output wire r,
2                   input wire c0,
3                   input wire c1,
4                   input wire w,
5                   input wire x,
6                   input wire y,
7                   input wire z );
8
9   wire w0, w1, w2, w3, w4, w5;
10
11   not t0( w0, c0 );
12   not t1( w1, c1 );
13
14   and t2( w2, w0, w1, w );
15   and t3( w3, c0, w1, x );
16   and t4( w4, w0, c1, y );
17   and t5( w5, c0, c1, z );
18
19   or t6( r, w2, w3, w4, w5 );
20
21 endmodule
```

Listing (Verilog)

```
1 module mux4_1bit( output wire r,
2                   input wire c0,
3                   input wire c1,
4                   input wire w,
5                   input wire x,
6                   input wire y,
7                   input wire z );
8
9   assign r = c1 ? ( c0 ? z : y ) :
10              ( c0 ? x : w );
11
12 endmodule
```


Part 3: high-level modelling (1)

Registers

► **Concept: registers** (resp. **register vectors**)

► are a form of **net** used to *store* values (i.e., retain state),

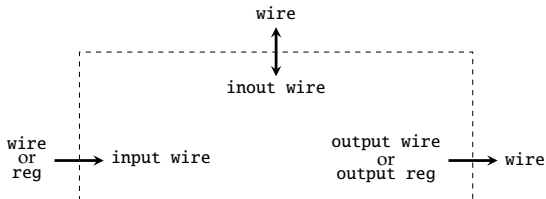
► e.g.,

- `reg w` $\Rightarrow$ an internal 1-bit register `w`
- `reg [ 3 : 0 ] x` $\Rightarrow$ an internal 4-bit register vector `x`

but, beware: registers *feel* analogous to C-style variables, but care is required re. use.

► Concept: module interfacing rules

Definition



which are *somewhat* intuitive when read as

input port : $\begin{cases} \text{externally} & \text{can be a wire or reg} \\ \text{internally} & \text{must be a wire} \end{cases}$

output port : $\begin{cases} \text{internally} & \text{can be a wire or reg} \\ \text{externally} & \text{must be a wire} \end{cases}$

i.e., we must be pessimistic when crossing the module boundary.

Part 3: high-level modelling (3)

Module implementation using behavioural-level Verilog

► Concept: behavioural-level module implementation

- describes module behaviour via
 - (at least partly) using **processes**,
 - each process is formed from **blocks** of **statements**,
 - each process is “executed” in parallel with the others once **triggered**.
- e.g.,

Listing (Verilog)
<pre>1 initial begin:id 2 ... 3 end</pre>

Listing (Verilog)
<pre>1 always begin:id 2 ... 3 end</pre>

shows the two process types

- **initial** ⇒ triggered only *once* (when the module is first powered-on)
- **always** ⇒ triggered in a *loop* (as long as the module is powered-on)

noting the right-hand case is problematic as is ...

► **Concept: behavioural-level module implementation**

- describes module behaviour via
 - (at least partly) using **processes**,
 - each process is formed from **blocks** of **statements**,
 - each process is “executed” in parallel with the others once **triggered**.
- e.g.,

Listing (Verilog)

```
1 always @ ( x ) begin
2   ...
3 end
```

Listing (Verilog)

```
1 always @ ( posedge x ) begin
2   ...
3 end
```

Listing (Verilog)

```
1 always @ ( negedge x ) begin
2   ...
3 end
```

shows processes that are triggered via a **sensitivity list**:

- @ (x) ⇒ triggers when x changes
- @ (posedge x) ⇒ triggers when x changes from 0 to 1 (a positive edge)
- @ (negedge x) ⇒ triggers when x changes from 1 to 0 (a negative edge)

- **Concept:** procedural assignment, e.g.,

Listing (Verilog)

```
1 module foo( input wire clk );  
2  
3   reg x, y;  
4  
5   always @ ( posedge clk ) begin  
6     x = 1'b0;  
7     y = 1'b1;  
8   end  
9  
10 endmodule
```

which differ from a continuous assignment: they

1. must use a register as the LHS (versus a wire), and
2. the LHS is assigned to whatever the RHS evaluates to when the statement executes (versus whenever the RHS changes).

- **Concept:** procedural assignment, e.g.,

Listing (Verilog)

```
1 module foo( input wire clk );
2
3   reg x, y;
4
5   always @ ( posedge clk ) begin
6     x = 1'b0;
7     y = 1'b1;
8   end
9
10 endmodule
```

which can introduce modelled **delay**:

- a **regular** delay, e.g.,

`#10 x = 0;`

means that, relative to the previous statement, this one will execute 10 time units later, whereas

- an **intra-assignment** delay, e.g.,

`x = #10 0;`

means that the RHS is evaluated straight away, but only assigned to the LHS after 10 time units.

- **Concept:** procedural assignment, e.g.,

Listing (Verilog)

```
1 module foo( input wire clk );
2
3   reg x, y;
4
5   always @ ( posedge clk ) begin
6     x = 1'b0;
7     y = 1'b1;
8   end
9
10 endmodule
```

which come in **blocking** or **non-blocking** variants:

- if we write

$$x = 0; y = 1;$$

then the assignment to y is blocked until the assignment to x is executed, whereas

- if we write

$$x <= 0; y <= 1;$$

then the assignments to x and y are executed in parallel.

Part 3: high-level modelling (5)

Module implementation using behavioural-level Verilog

- **Concept:** conditional statements, e.g.,

Listing (Verilog)

```
1 module bar( input wire clk );
2
3   reg x, y;
4
5   always @ ( posedge clk ) begin
6     if( x == 1'b0 ) begin
7       y = 1'b1;
8     end else begin
9       y = 1'b0;
10    end
11  end
12
13 endmodule
```

Listing (Verilog)

```
1 module baz( input wire clk );
2
3   reg x, y;
4
5   always @ ( posedge clk ) begin
6     case( x )
7       1'b0 : y = 1'b1;
8       1'b1 : y = 1'b0;
9       default : y = 1'b0;
10    endcase
11  end
12
13 endmodule
```

noting that

- it starts to be attractive to leave out the begin and end keywords for single line blocks; this is equivalent to the same rule with “curly braces” in C,
- we need to take care with unknown or high impedance values; if x doesn't equal 0 or 1 you may get unexpected behaviour.

Part 3: high-level modelling (6)

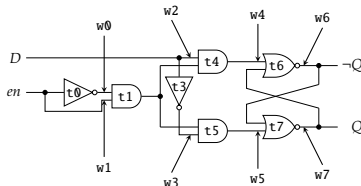
Module implementation using behavioural-level Verilog

► Example:

Listing (Verilog)

```
1 module dff( input wire en,
2
3             input wire D,
4             output wire Q );
5
6     wire w0, w1, w2, w3, w4, w5, w6, w7;
7
8     not t0( w0, en );
9     and t1( w1, w0, en );
10
11     buf t2( w2, D );
12     not t3( w3, w2 );
13
14     and t4( w4, w2, w1 );
15     and t5( w5, w3, w1 );
16
17     nor t6( w6, w4, w7 );
18     nor t7( w7, w5, w6 );
19
20     buf t8( Q, w7 );
21
22 endmodule
```

Circuit



Part 3: high-level modelling (6)

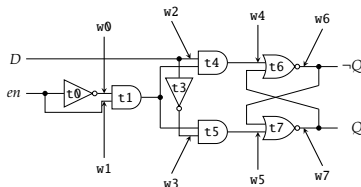
Module implementation using behavioural-level Verilog

► Example:

Listing (Verilog)

```
1 module dff( input wire en,  
2  
3           input wire D,  
4           output wire Q );  
5  
6   reg t;  
7  
8   assign Q = t;  
9  
10  always @ ( posedge en ) begin  
11    t = D;  
12  end  
13  
14 endmodule
```

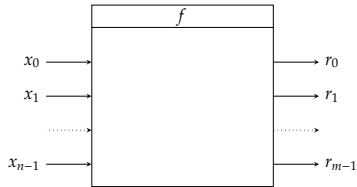
Circuit



Part 4: development concepts (1)

Testing

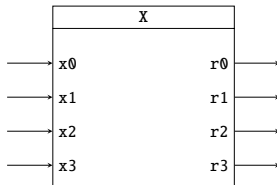
- **Concept:** test stimulus (or test harness).



Part 4: development concepts (1)

Testing

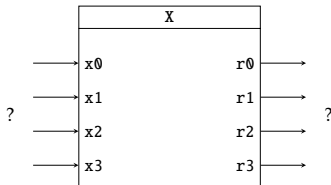
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Part 4: development concepts (1)

Testing

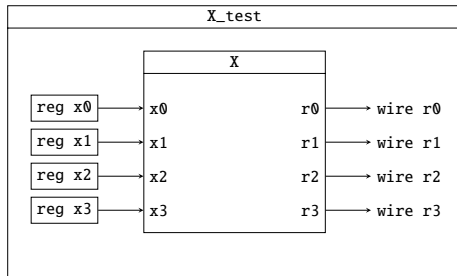
- **Concept:** test stimulus (or test harness).

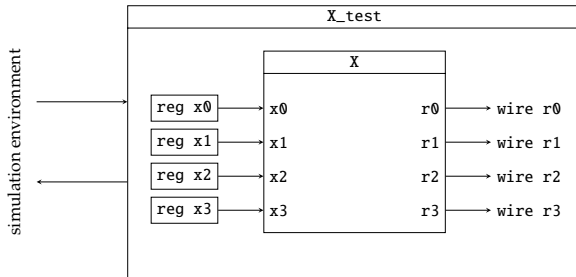


Part 4: development concepts (1)

Testing

- **Concept:** test stimulus (or test harness).



► **Concept: test stimulus (or test harness)**

noting that **X_test**

- is termed a (or the) **top-level module** in the sense it has no inputs or outputs,
- can interact with the simulation environment is via **system tasks** and **system functions**, e.g.,
 - **\$random** ⇒ generates random value(s)
 - **\$display** ⇒ displays value(s) synchronously
 - **\$monitor** ⇒ displays value(s) asynchronously
 - **\$stop** ⇒ halt current simulation
 - **\$finish** ⇒ terminate current simulation
- will apply some form of **test strategy** to the instance of **X**.

► Example:

Listing (Verilog)

```
1 module fa_test();
2
3     wire t_co,      t_s;
4     reg  t_ci; t_x, t_y;
5
6     fa t( .co( t_co ), .s( t_s ), .ci( t_ci ), .x( t_x ), .y( t_y ) );
7
8     initial begin
9         #10 t_ci = 1'b0; t_x = 1'b0; t_y = 1'b0;
10        #10 $display( "co=%b s=%b ci=%b x=%b y=%b", t_co, t_s, t_ci, t_x, t_y );
11        #10 t_ci = 1'b0; t_x = 1'b0; t_y = 1'b1;
12        #10 $display( "co=%b s=%b ci=%b x=%b y=%b", t_co, t_s, t_ci, t_x, t_y );
13        #10 t_ci = 1'b0; t_x = 1'b1; t_y = 1'b0;
14        #10 $display( "co=%b s=%b ci=%b x=%b y=%b", t_co, t_s, t_ci, t_x, t_y );
15        #10 t_ci = 1'b0; t_x = 1'b1; t_y = 1'b1;
16        #10 $display( "co=%b s=%b ci=%b x=%b y=%b", t_co, t_s, t_ci, t_x, t_y );
17
18        #10 $finish;
19    end
20
21 endmodule
```


► Example:

Listing (Verilog)

```
1 module fa_test();
2
3     wire t_co,      t_s;
4     reg  t_ci; t_x, t_y;
5
6     fa t( .co( t_co ), .s( t_s ), .ci( t_ci ), .x( t_x ), .y( t_y ) );
7
8     initial begin
9         $monitor( "co=%b s=%b ci=%b x=%b y=%b", t_co, t_s, t_ci, t_x, t_y );
10
11         $monitoron;
12
13         #10 t_ci = 1'b0; t_x = 1'b0; t_y = 1'b0;
14         #10 t_ci = 1'b0; t_x = 1'b0; t_y = 1'b1;
15         #10 t_ci = 1'b0; t_x = 1'b1; t_y = 1'b0;
16         #10 t_ci = 1'b0; t_x = 1'b1; t_y = 1'b1;
17
18         #10 $monitoroff;
19         $finish;
20     end
21
22 endmodule
```

Part 4: development concepts (4)

“Quality-of-life” features

- **Concept:** a “better” model $\leadsto$ greater **generalisation, maintainability**, etc.

1. We can use a **pre-processor** to

- define symbolic names for literals, e.g.,

```
`define TRUE 1
```

then

- use those symbolic names e.g.,

```
assign r = x ^ `TRUE;
```

2. We can use **named ports** to avoid misconnections, e.g.,

```
fa t( .co(a), .s(b), .ci(c), .x(d), .y(e) );
```

is the same as

```
fa t( .co(a), .s(b), .ci(c), .y(e), .x(d) );
```

3. We can **parametrise** modules:

- their interface and behaviour is specified by a *single* fragment of source code,
- each instance can be altered to suit the context it is used in.

4. We can **generate** “regular” fragments of source code (cf. meta-programming, versus “copy and paste”).

► Take away points:

1. In essence, a HDL model is just machine-readable short-hand for a design you could develop and reason about on paper.
2. It's important to remember that, despite appearances,

HDL modelling $\neq$ software development,

i.e., you *still* have to understand the fundamentals and “think in hardware”.

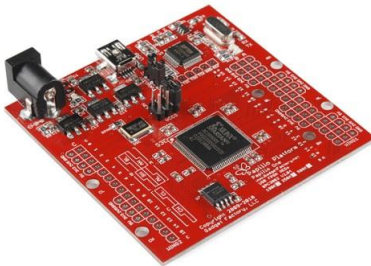
3. Even within this unit, HDLs offer various useful properties, e.g.,

- adopt a more accurate experimental approach to design,
- deal with designs of a larger scale,
- interface with other concepts (e.g., verification),
- ...

so some up-front, invested effort *could* pay off ...

Conclusions

- **Example:** Field Programmable Gate Arrays (FPGAs).



- ▶ basic idea is that the hardware fabric is reconfigurable, so, in a sense,

hardware
(e.g., ASIC)

hybrid
(e.g., FPGA)

software
(e.g., micro-processor)

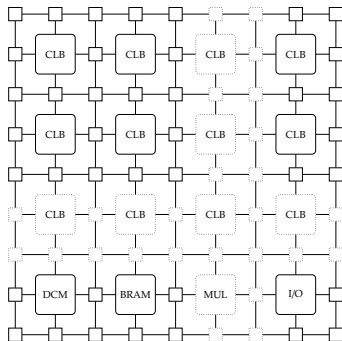


- ▶ and therefore offers a trade-off:

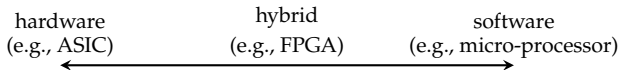
efficiency $\simeq$ hardware
flexibility $\simeq$ software

Conclusions

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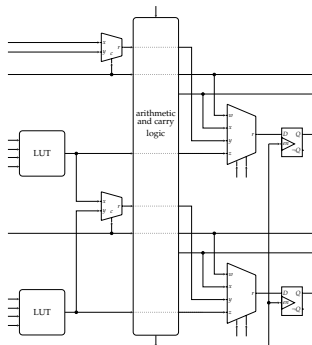


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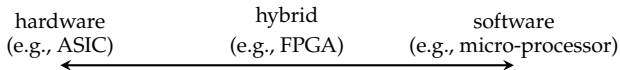
efficiency $\approx$ hardware
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Conclusions

► Example: Field Programmable Gate Arrays (FPGAs).



- basic idea is that the hardware fabric is reconfigurable, so, in a sense,



- and therefore offers a trade-off:

efficiency $\approx$ hardware
flexibility $\approx$ software

Additional Reading

- ▶ *Wikipedia: Hardware Description Language (HDL)*. URL: https://en.wikipedia.org/wiki/Hardware_description_language.
- ▶ *Wikipedia: Verilog*. URL: <https://en.wikipedia.org/wiki/Verilog>.
- ▶ S. Palnitkar. *Verilog HDL: A Guide in Digital Design and Synthesis*. 2nd ed. Prentice Hall, 2003.
- ▶ D. Page. “Chapter 3: Hardware design using Verilog”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009.

References

- [1] *Wikipedia: Hardware Description Language (HDL)*. URL: https://en.wikipedia.org/wiki/Hardware_description_language (see p. 55).
- [2] *Wikipedia: Verilog*. URL: <https://en.wikipedia.org/wiki/Verilog> (see p. 55).
- [3] D. Page. “Chapter 3: Hardware design using Verilog”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009 (see p. 55).
- [4] S. Palnitkar. *Verilog HDL: A Guide in Digital Design and Synthesis*. 2nd ed. Prentice Hall, 2003 (see p. 55).
- [5] *IEEE Standard for Verilog Hardware Description Language*. Institute of Electrical and Electronics Engineers (IEEE) 1364-2005. 2006. URL: <http://standards.ieee.org> (see p. 2).